ROCKET LAUNCH-INDUCED VIBRATION AND IGNITION OVERPRESSURE RESPONSE

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Abstract

Rocket-induced vibration and ignition overpressure response environments are predicted in the low-frequency (5 to 200 hertz) range. The predictions are necessary to evaluate their impact on critical components, structures, and facilities in the immediate vicinity of the rocket launch pad.

INTRODUCTION

The launch of a rocket generates intense environment exposing the spacecraft with its irreplaceable human cargo, extremely sensitive payload, and launch-critical ground equipment to several types of static and dynamic stress. At lift-off the thrust of the rocket motors and resulting acceleration of the launch vehicle impose a large steady-state load. Significant transients due to engine ignition produce vibration over a wide range of frequencies. However, a particularly serious source of vibration is very high-amplitude acoustic noise generated by the propulsion system of the first-stage main engines at lift-off. The noise reflects upward from the ground and envelopes the spacecraft and launch pad equipment and structures. This lasts about 10 seconds until the rocket clears the pad.

The loads and vibration may cause structural damage to the vehicle, its payload, or ground equipment failure, consequently leading to partial or total loss of mission objectives. A 1971 NASA study [1] concluded that the vibration/acoustic launch environment was estimated to account for 30 to 60 percent of the first-day space failures. This statistic serves as a caution to the analysts and designers involved in the planning and operation of newer launch facilities. The actual first-day space failures have been less frequent. The idea is to prevent such failures via careful assessment of acoustic impact early in the design cycle and, more importantly, prior to the actual fabrication and installation.

BACKGROUND

As the United States space program expands, many hazards (operational as well as malfunctions) pertaining to the launch site equipment and facility design come under greater scrutiny. In addition to the many types of hazards, such as blast, seismic, nuclear, toxic, lightening, etc., the effect of large sound and vibration fields generated every time the rocket engines are fired becomes significantly more important.

Acoustic noise is an unavoidable byproduct generated by the firing of rocket engines. It also leads to significant vibrations of critical structures near the launch or static test stand. Figures 1 and 2 provide a qualitative overview of the impact of acoustic/vibration fields on ground equipment and structures [2].

The airborne sound acting on the structural elements above the ground excites a typical building or structure in the vicinity of the launch pad. A part of this sound energy is transmitted into the building interior via any opening in the walls and reradiation from the vibrating walls. Unless the building structure is acoustically isolated, a significant portion of acoustic energy may propagate into the building interior.

Ground vibrations, generated by the exhaust stream of the rocket engine that impinges off the deflector, can also be transmitted structurally from the launch pad to the parts of the building below ground, thereby exciting the rest of the building into vibrations. Airborne and structureborne noise and vibration will affect equipment and machinery located inside the structure.

Continuous exposure to vibration and an ignition overpressure environment may cause serious structural and equipment failures resulting in impairment of function or complete mission failure. Therefore, knowledge of the fundamental factors governing the vibratory source characteristics and their subsequent responses is paramount to the designer of launch pad equipment, structures, and facilities [3].

METHOD OF ANALYSIS

The launch pad complex typically comprises a hardstand concrete mount with fixed service structure (FSS) and rotating service structure (RSS) placed in strategic locations for access to the launch vehicle (figure 3). Fuel, oxidizer, high-pressure gas, and electrical and pneumatic umbilical lines connect the launch vehicle with the ground support equipment and are routed through the FSS and RSS. Access and servicing at the launch pad is provided through various swing arms for a variety of activities, including electrical power, hydrogen vent, fuel cell servicing, life support functions, maneuvering payloads, venting hazardous gases, and propellant loading. Prediction of vibratory response could be accomplished through both empirical and analytical approaches. The analytical approach herein utilizes the concept of a generalized form of joint acceptance procedure [4] for vibration and ignition overpressure prediction.

Vibration Response

First, using Ansys Finite Element (FE) code, a model of the FSS was developed inclusive of the primary structure and the attached swing arms (figure 4). The model is composed of over 500 nodes and 2000 elements. Since understanding the vibratory behavior of the structure at key locations where launch-critical components would be placed was of essence, equipment of consequence (along with siding) was added as lumped mass. Boundary conditions involved constraining all translation and rotation degrees of freedom at the base of the structure.

Natural frequencies and mode shapes were computed in the low frequencies between 5 and 200 hertz. The vibration response power spectral densities were then computed using the following equation after defining the joint acceptances and appropriate surface areas affected by the rocket-induced acoustics. Figure 5 includes the predicted vibration spectra for a location on the FSS in a horizontal direction. Similar predictions were made at several other zones on the FSS and in the vertical direction.

$$W_{\ddot{x}}(i,f) = \frac{W_p(f)}{g^2} \sum_{i=1}^{Modes} \frac{J_i^2 A_i^2 |H_i(f)|^2 \phi_i^2 f^4}{M_i^2 f_i^4}$$

$$W_{\ddot{x}}(i,f) = \text{acceleration PSD}$$
$$W_p(f) = \text{acoustic pressure PSD}$$
$$g = \text{acceleration of gravity}$$
$$J_i^2 = \text{joint acceptance for i mode}$$
$$A_i = \text{correlation area for i mode}$$
$$H_i(f) = \text{dynamic magnification function for i mode}$$
$$\phi_i = \text{mode shape}$$
$$f = \text{frequency}$$
$$f_i = \text{frequency i mode}$$
$$M_i = \text{mass i mode}$$

Ignition Overpressure

Ignition overpressure peaks are a result of using solid rockets rather than liquid rockets. It represents a shock loading to the structures and equipment located on the launch pad. Solid fuels are superior to liquid fuels in terms of their high-thrust capability during the early phase of launch. However, their main drawback is the inability to throttle the engine once ignited. The generated shock loading can lead to fracture or even catastrophic failure.

The methodology for prediction of the ignition overpressure response follows a similar procedure followed earlier. Using the computed natural frequencies and mode shapes from the modal model, appropriate joint acceptance factors (J) and surface areas exposed to the ignition overpressure peaks are selected. Then, the following equation is used to derive the peak acceleration response spectrum to IOP, in the X, Y, and Z directions for FSS and any other areas of interest. A sample prediction is included in figure 6.

$$\ddot{x}_{peak}(f_i) = J_i A_i q_{max_i}(f_i) PF_i \phi_i$$

$$\ddot{x}_{peak}(f_i) = \text{peak acceleration for mode i}$$
$$J_i = \text{joint acceptance for mode i}$$
$$A_i = \text{correleation area for mode i}$$
$$q_{max_i}(f_i) = \text{maximum modal coordinate for mode i}$$
$$PF_i = \text{participation factor for mode i}$$
$$\phi_i = \text{mode shape i}$$

Response modal coordinate is given by:

$$q_{max_i} = max(q_i(t))$$

$q_i(t)$ = solution of the SDOF equation for mode i versus time

Note: SDOF equation is solved using piecewise linear interpolation and recurrence relations from [5].

SDOF Modal coordinate equation:

$$\frac{p(t)}{M_i} = \ddot{q}_i(t) + 4\pi\zeta f_i \dot{q}_i(t) + 4\pi^2 f_i^{\,2} q_i(t)\,\mathrm{P(t)}$$

CONCLUSION

The paper summarizes the effort undertaken to address the worst-case vibration and ignition overpressure responses generated by the launch of rockets on pad equipment and structures. Impact of launch-induced acoustic noise and its influence on the design of ground support equipment is vital to mission success [6].

5. REFERENCES

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6. Acoustic and Vibration Environments and Test Specification Levels Ground Support Equipment Launch Complex 39, Document SP-4-38-D, NASA, July 1964.

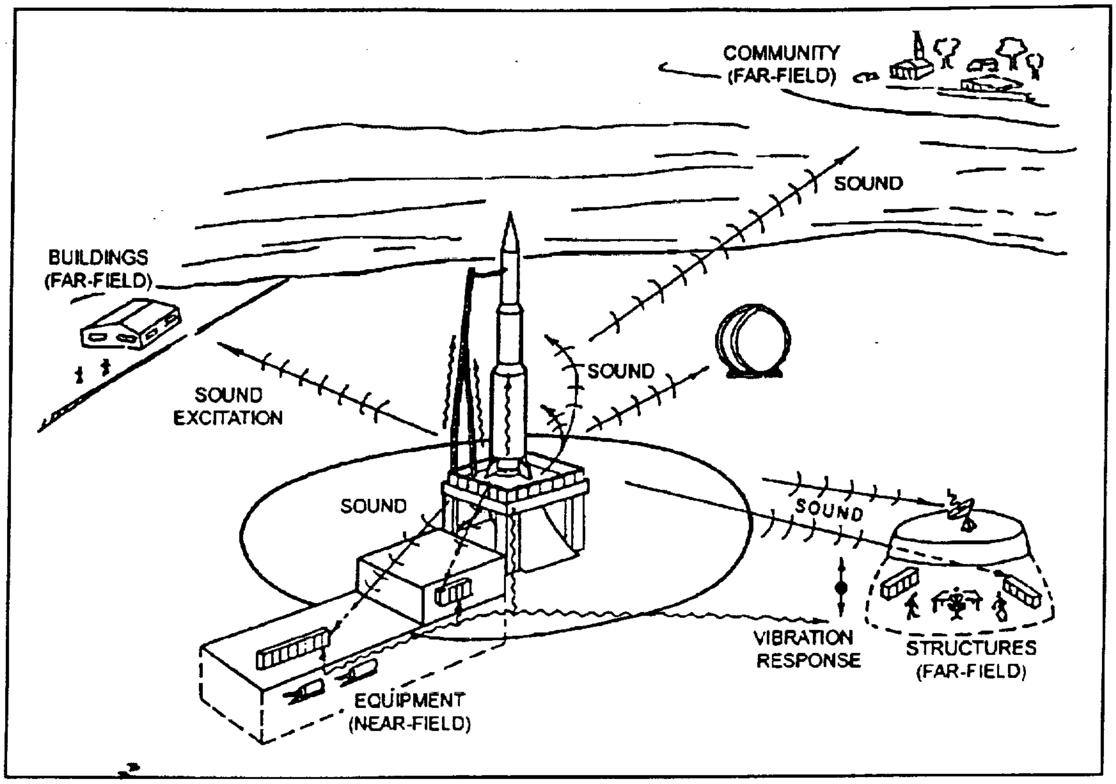

Figure 1. Rocket Noise and Vibration Affected Areas (NASA-CR-50101)

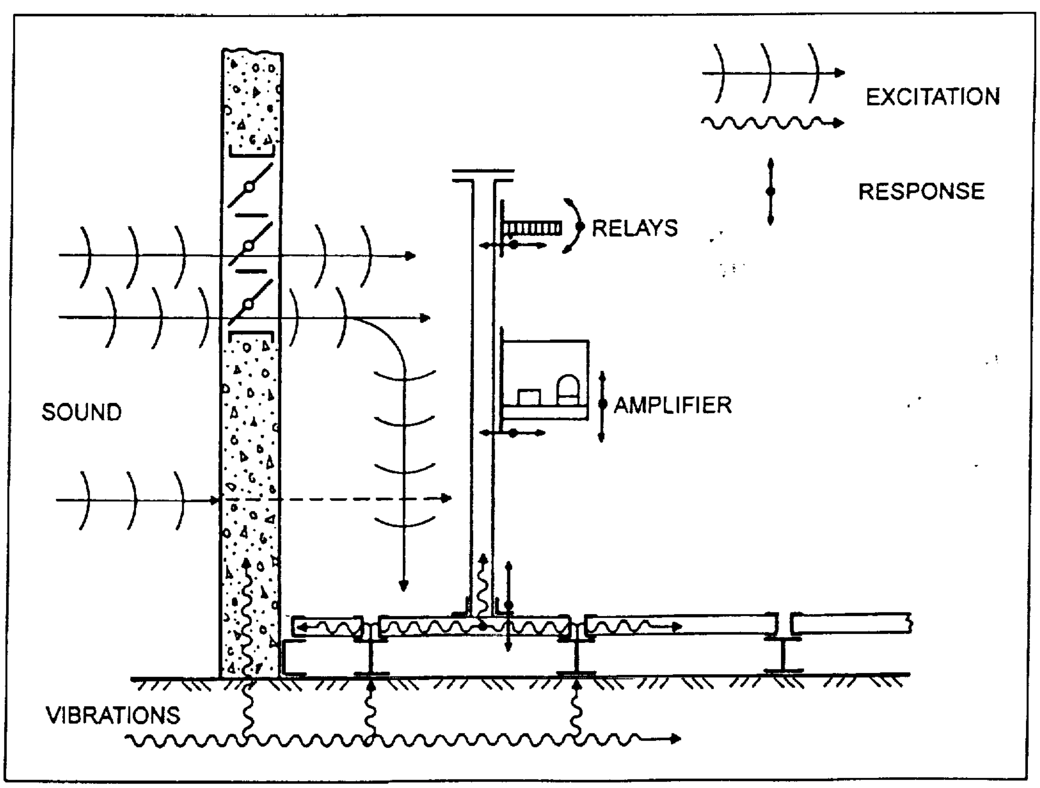

Figure 2. Excitation and Response of Launch Critical Equipment (NASA-CR-50101)

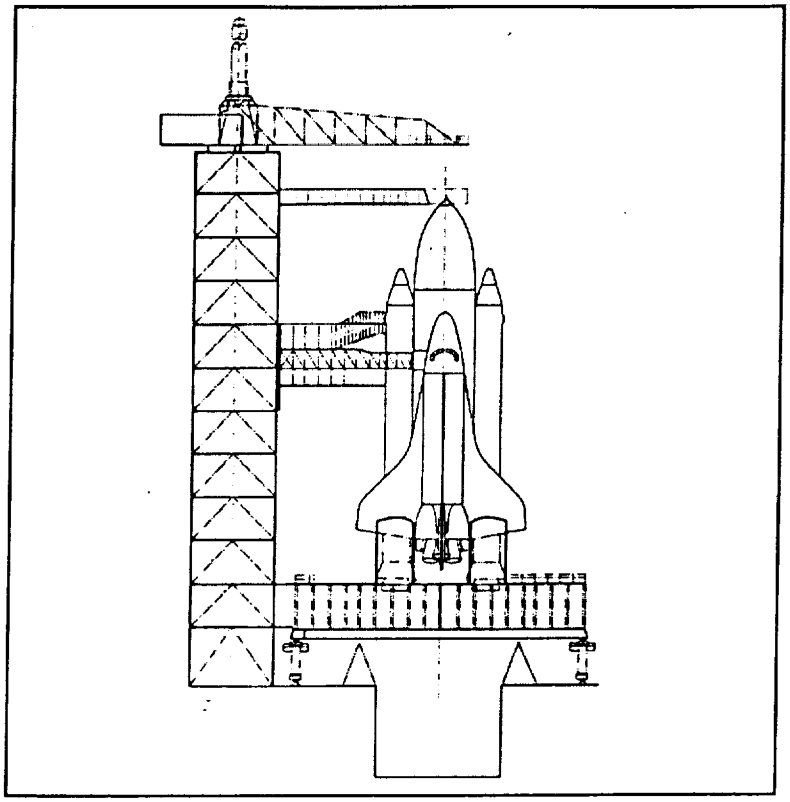

Figure 3. Space Shuttle Launch Pad

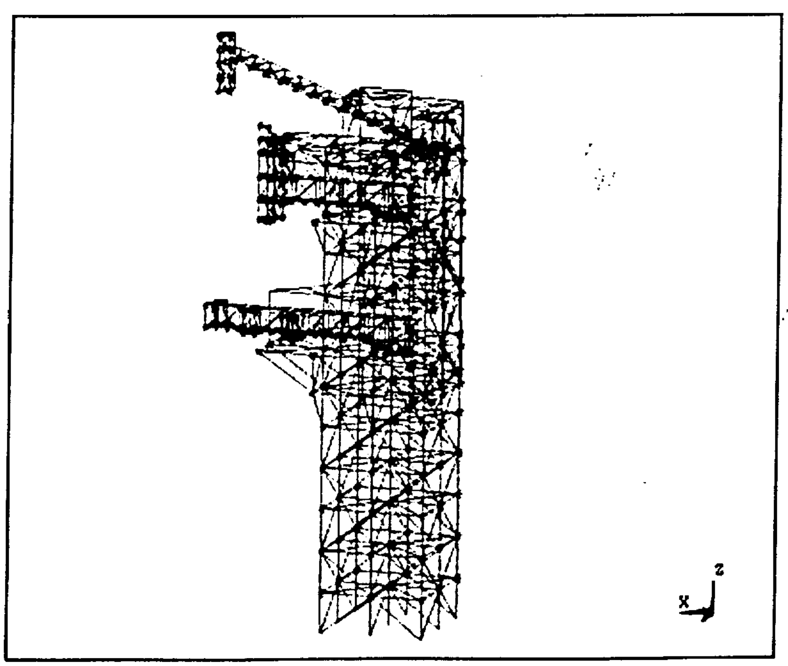

Figure 4. Fixed Service Structure (FSS) and Related Swing Arms

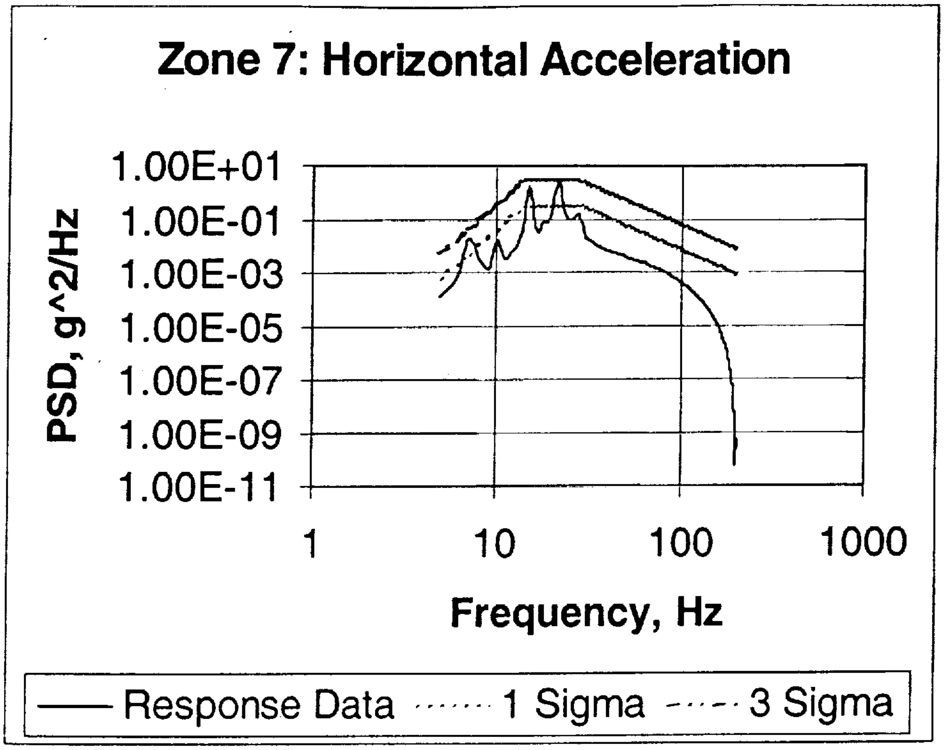

Figure 5. Predicted Vibration Response on the FSS

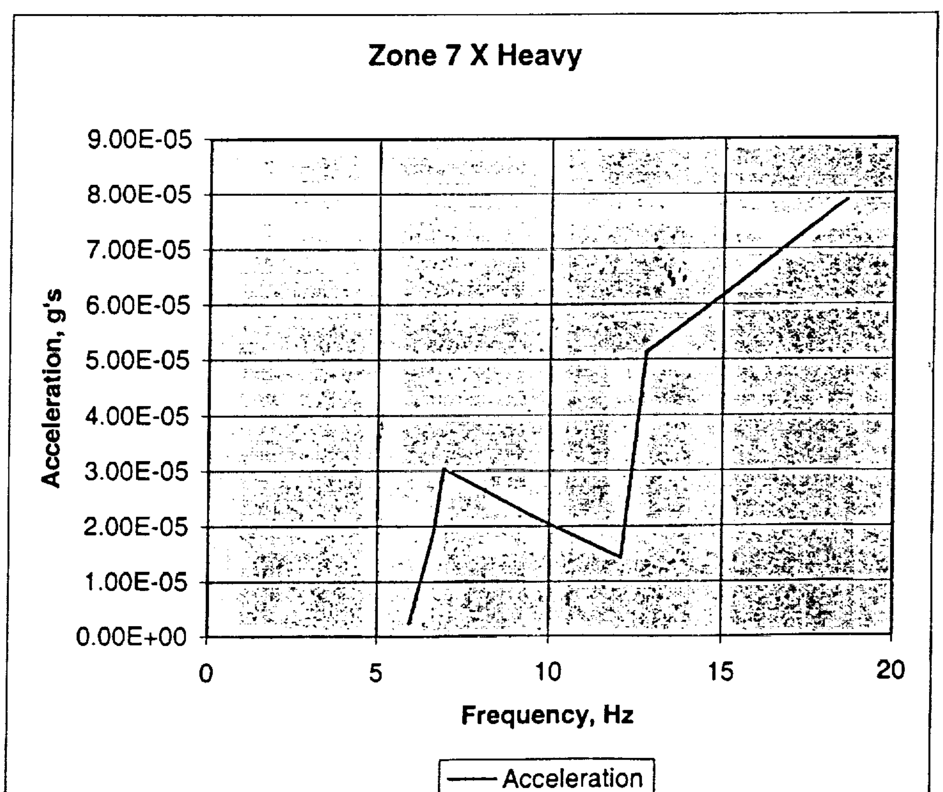

Figure 6. Predicted Ignition Overpressure Response on the FSS